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A smeared-out material model predicting compressive failure of composites

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Summary

The cost efficiency of wind turbines has during the last 30 years been improved by increasing the length of of the wind turbine blades. Increasing length does also mean higher weights and loading of the blade material. Glass fiber composites has been the dominating material used in wind turbine blades, but for the longest blades, 60 meters with a weight on 15 to 18 metric tons, carbon fiber composts has been used either as a hybrid together with glass fibers or as a pure carbon fiber composites in central parts of the blades. As a contrast to glass fiber composites, the design criteria in carbon fiber composites are often specified by the compression strength of the composite component. This is due to the fact that the compression strength of unidirectional composites is as low as 50 to 60 percent of the tensile strength. One important compressive failure mode in composite is kink-band formation which for a great deal is governed by the waviness of the fibers and the yielding properties of the matrix material. Therefore, in order to make proper simulation of the failure modes in composites, it is necessary to take these effects into account. One approach is to model the actual fiber/matrix system using a micromechanical based finite element model. For realistic composite structures with large number of fibers, approaches which will result in extremely large numerical models including a great deal of unwanted details. An alternative is to base the simulation on a smeared out composite model where the nonlinear properties of the constituents are taken into account. A finite element implementation of such a model is presented. The model are implemented as an UMAT user subroutine in the commercial finite element program Abaqus and used to predict kink-band formation in composite structures. Kink-band predictions are demonstrated in a simple square block of UD composite material under axial compression. The importance of the plasticity of the matrix material and small imperfection in the fiber directions on the compression strength are demonstrated.

1 The material model and the implementation

A plane version of a smeared out composite material law is implanted. The material model and the implementation is described in detail in [1,2] and [3] and will in the following only be described briefly. A plane strain formulation is implemented where the two constituents is modeled following a time-independent power-law hardening elastic-plastic material law

$$\varepsilon = \frac{\sigma}{E} \text{ for } \sigma \le \sigma_y \qquad \text{and} \qquad \varepsilon = \frac{\sigma_y}{E}\left[\frac{1}{n}\left(\frac{\sigma}{\sigma_y}\right)^n - \frac{1}{n} + 1\right] \text{ for } \sigma > \sigma_y \tag{1}$$

In equation (1); E , σ_y and n denotes the Youngs modulus, the initial yield stress and the hardening exponent, respectively. The matrix and fiber material is considered as two independent non-linear materials with individual material parameters. The composite material is in total given by 9 material parameters

$$E^f,\, E^m,\, \nu^f,\, \nu^m,\, \sigma_y{}^f,\, \sigma_y{}^m,\, n^f,\, n^m,\, c_f \tag{2}$$

defining the Young modulus, the Poisson's ratio, the initial yield stress of the two constituents as well as the volume fraction of the fibers, respectively for the two constituents $()^f$ and $()^m$.

The two non-linear materials are in each increment combined in a smeared out constitutive formulation of the composite using the Voigt and Reuss assumptions:

- Voigt: Material lines parallel with the fibers are subject to a common stretching and rotation
- Reuss: Planes parallel with the fibers transmit identical tractions

Formulated in a framework valid for finite strains and rotations it is possible based on these assumptions to derive the constitutive relation between the Cauchy stress and the strains on incremental form

$$\dot{\sigma}_{ij} = L_{ijkl}\dot{\varepsilon}_{kl} \tag{3}$$

where the increments of the strains are given by the gradient of the velocity components v_i ,

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \tag{4}$$

Using the approximation that the component of the Kirchhoff stresses $\tau_{ij} \approx \sigma_{ij}$, the in-plane components of L_{ijkl} can be written as

$$L_{ijkl} = C_{ijkl} + \tfrac{1}{2}\delta_{il}\sigma_{kj} + \tfrac{1}{2}\delta_{ik}\sigma_{lj} + \tfrac{1}{2}\sigma_{il}\delta_{kj} - \tfrac{1}{2}\sigma_{ik}\delta_{lj}; \quad i, j, k, l \in \{1,2\}\,. \tag{5}$$

where δ_{ij} is Kronecker's delta and where the tensor C_{ijkl} describe the constitutive relations between the nominal stress rate and the velocity components

$$\dot{s}_{ij} = C_{ijkl} v_{l,k} \tag{6}$$

The components of C_{ijkl} are found from the mixture of fiber and matrix properties, see [1].

The model is implemented in the commercial finite element code Abaqus through the user subroutine UMAT. The UMAT routine utilizes a total of 16 state variables defined in every integration point and updated after each increment. The 16 state variables are the instantaneous yield stress for the fiber and matrix material, the effective plastic strain in the fiber and the matrix material, two variables indicating whether or not the material yields in the fiber and matrix material in the current increment, the in-plane stress tensor components for the fiber and matrix material, the out of plane stress component, σ_{33} , for the fiber and matrix material and the initial and the current rotation of the fibers.

2 Model

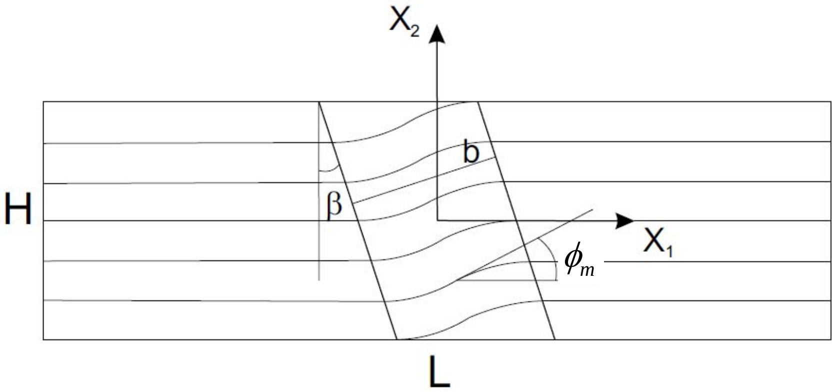

Fig. 1: The imperfect uni-directional fiber-layup

The implementation is used to demonstrate the formation of a kink-band in a block of uni-directional composite material loaded under axial compression. The block has the size $H = 3$ and $L = 10$. A small initial waviness as shown in Fig. 1 is introduced into the model using the Abaqus user subroutine ORIENT. The size and shape of the imperfection are given by the parameters b, β and ϕ_m where the most important imperfection parameter, the angle ϕ_m is the maximum waviness of the fiber direction in the middle of the band defined by b and β.

The material parameters of the matrix material is given by

$$\frac{\sigma_y{}^m}{E_m} = 0.13,\ \nu^m = 0.356,\ n^m = 4.5 \tag{7}$$

which quite well fit the mechanical behavior of a PEEK thermoplastic matrix material, [4]. For simplicity the fiber material is taken as a linear elastic material. The two stiffness ratios

$$\frac{E^f}{E^m} = 35 \quad \text{or} \quad \frac{E^f}{E^m} = 100 \tag{8}$$

are used where the first correspond to a glass fiber reinforced polymer while the second one corresponds to a carbon fiber reinforced polymer. The fiber volume fraction was chosen to $c^f = 0.6$.

3 Results

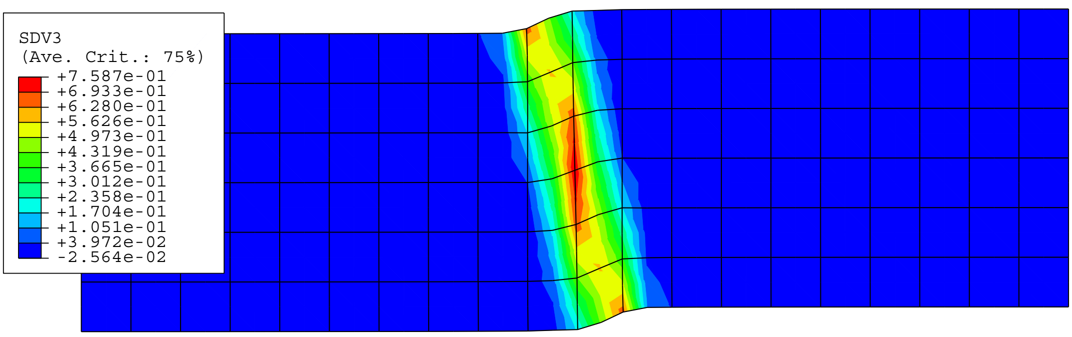

Fig. 2: Contour-plot of the effective plastic strains in the matrix material

Fig. 2 show the deformed mesh and the contours of the effective plastic strain for the case $E^f/E^m = 35$. A small initial imperfection was chosen with $\phi_m = 2^\circ$, $\beta = 5^\circ$ and $b = 2$. Only the initial fiber waviness misalignment ϕ_m is expected to have a significant influence on the kink-band formation [3]. Actually, even for a large initial angle $\beta = 30^\circ$ the final kink-band is found to be similar to the one shown in Fig. 2.

The resulting load versus shortening curve for the case in Fig.2 together with other cases are shown in Fig. 3. There is observed a pronounced snap-back behaviour resulting in a very imperfection sensitive load carring capacity. The snap-back behaviour is in Abaqus modelled using the Riks method, see e.g. [5]. In addition to the imperfection sensitivity, the compression strength is found to be highly dependent on the plasticity of the matrix material. Actually, a suppressed plastic deformation of the matrix material will lead to a case with no kink-band formation. Instead, the block of material will first fail at a much higher load corresponding to the Euler buckling mode [6]. Eventhough the finite element simulation is based on a smeared out composite material law, the observation is quite similar to predictions found in a full micromechanical simulations [7].

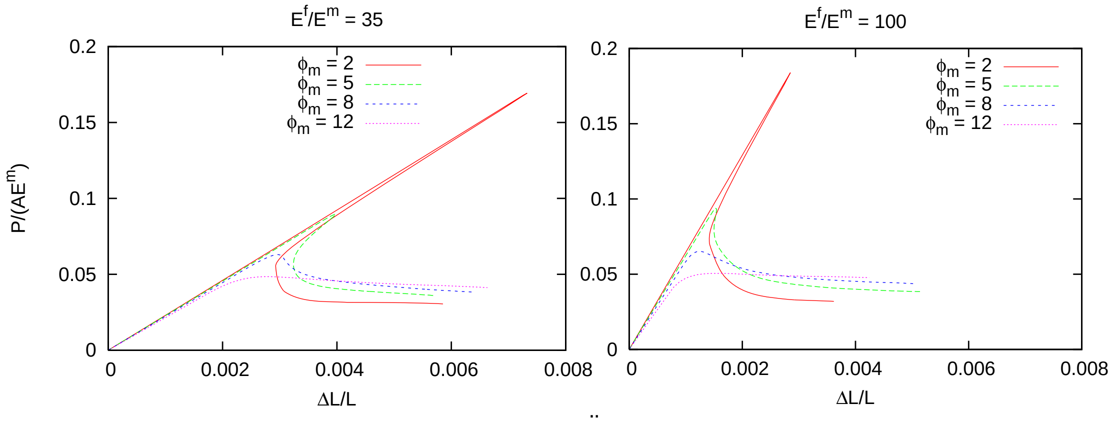

Fig. 3: Kink band formation including plastic deformation in the matrix material

4 Conclusion

Based on a smeared out non-linear composite material law implemented in the commercial finite element software, Abaqus, realistic kink-band formation is predicted. Even though the case studied is a rather simple “block of material” under compression, the finite element model implementation is straightforward to use on more complex and realistic cases. E.g. optimizing thin-walled structures against buckling will often require thicker shell walls were a kink-band can be considered as the next most critical failure mode. A failure mode, which will not be taken into account in a conventional linear elastic composite model. On the other hand, a full micromechanical model will often require extremely large models with a great deal of unwanted details. Therefore, for cases like this, a non-linear composite law as the one presented could be the right choice.

5 Literature

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